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Regional dust model performance during SAMUM 2006

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[1] Traditionally there has been a lack of intensive measurements directly over dust sources for validating the accuracy of dust models. Utilizing the valuable and unprecedented SAMUM 2006 field campaign dust dataset in North Africa, we assess the performance and discuss the limitations of a state-of-the-art dust regional model to reproduce the complex dust patterns encountered during the campaign. The DREAM model operational forecast version during SAMUM 2006 (OPER) and an updated model version (RESH) are run and compared. RESH reproduces the general Saharan dust pattern, whereas OPER shows limitations to quantitatively reproduce dust optical properties over sources and after long range transport simultaneously. Dust transport in RESH with enhanced number size bin distribution is proven to be more efficient and adequate. The modeled vertical extinction coefficient captures fairly well lidar observations. While particle number size distribution is consistently reproduced at surface level, we find significant underestimation in the middle troposphere for large particles. Occasionally, synoptic scale meteorology remains unsatisfactorily captured leading to errors in the location and intensity of dust emission and subsequent transport. **Citation:** Haustein, K., C. Pérez, J. M. Baldasano, D. Müller, M. Tesche, A. Schladitz, M. Esselborn, B. Weinzierl, K. Kandler, and W. von Hoyningen-Huene (2009), Regional dust model performance during SAMUM 2006, *Geophys. Res. Lett.*, *36*, L03812, doi:10.1029/2008GL036463.

1. Introduction

[2] Significant impacts and feedbacks within the Earth System are related to the transport and deposition of mineral dust emitted from arid and semi-arid areas worldwide. In this context, during the last two decades, substantial efforts have been devoted to develop global and regional models for the simulation and the prediction of the atmospheric mineral dust cycle. Still nowadays, location, intensity and size distribution of dust emissions remain as the highest sources of uncertainty in current modeling systems [*Tegen et al.*, 2006].

[3] Since we are lacking intensive measurements directly over dust sources a German research consortium recently carried out the SAharan Mineral dUst experiMent (SAMUM), providing a valuable and unprecedented dust dataset for North Africa [*Heintzenberg*, 2009] that allows for a detailed evaluation of dust models. The first phase of the campaign (SAMUM-I) took place from May 10th to June 7th 2006 at two sites in Morocco accompanied by several overflights of two research aircraft. The observational dataset includes ground-based (Raman and backscatter) and onboard High-Spectral-Resolution Lidar (HSRL) profiles, surface and tropospheric dust size distribution, aerosol mass concentration and chemical composition, dust sample microscopic qualities, optical properties, sun photometer data and basic meteorological parameters [*Esselborn et al.*, 2009; *Tesche et al.*, 2009; *Kandler et al.*, 2009; *Müller et al.*, 2009a; *Schladitz et al.*, 2009; *Weinzierl et al.*, 2009]. During the campaign, the Dust Regional Atmospheric Modeling System (DREAM) was used as a forecast tool for planning the schedule of the overflights. DREAM is a well established forecast model delivering daily products for North Africa, Europe, Middle East and Asia http://www.bsc.es/projects/earthscience/DREAM/). Main objective of this contribution is to verify the performance and to discuss the limitations of the operational [*Nickovic et al.*, 2001] and an updated research model version [*Pérez et al.*, 2006b] in order to capture the complex dust emission pattern encountered during the campaign.

2. Methodology

2.1. The DREAM Model Setup

[4] The DREAM regional dust model is embedded on-line into the NCEP/Eta atmospheric model. The operational model version (hereinafter referred to as OPER; see detailed description by *Nickovic et al.* [2001]) considers four dust particle size categories with radii of 0.73, 6.1, 18, and 38 μm. The updated research model version (hereinafter referred to as RESH; described in detail by *Pérez et al.* [2006b]) includes a high resolution size distribution within the 0.1–10 μm radius range according to *Tegen and Lacis* [1996] and dust radiative feedback. RESH relies on an enhanced high resolution USGS (1 km) vegetation dataset. The model is initialized with 24-hourly updated NCEP (National Centers for Environmental Prediction) $1° \times 1°$ analysis data with a 'dust spin up' of 72 hours in advance. For OPER the horizontal (1/3°) and vertical (24 z-levels) resolution is kept. The latitudinal forecast domain covers 15°N to 60°N, the longitudinal 25°W to 50°E. In case of RESH a higher horizontal resolution (1/6°) is applied.

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2.2. Retrieval of Aerosol Optical Depth

[5] Aerosol optical depth (AOD) at 440 nm or 500 nm and Ångström exponent (440–870 nm) are retrieved at 7 AERONET (AErosol RObotic NETwork) stations and Zagora by means of sun photometers/sky radiometers [*von Hoyningen-Huene et al.*, 2009]. For this study level 2.0 data are used exclusively. The calculation of the AOD in DREAM differs between OPER and RESH. In the first case, we coarsely estimate the AOD assuming and average specific cross section of 0.56 m^2/g [*Pérez et al.*, 2006a]. In case of RESH, within each transport bin, dust is assumed to have time invariant, sub-bin lognormal distribution employing the transport mode with mass median diameter of 2.524 mm and geometric standard deviation 2.0. Extinction efficiencies for each bin are calculated through a Mie code [*Pérez et al.*, 2006b] assuming spherical dust particles.

2.3. Satellite and Monitoring Products

[6] In order to qualitatively compare the spatio-temporal distribution of the modeled AOD, satellite based remote sensing retrievals are used. The OMI AI (Ozone Monitoring Instrument Aerosol Index) is a qualitative measure of the presence of UV absorbing aerosol particles including dust, computed from an ozone retrieval algorithm based on measured backscattered radiances in the near UV spectrum. The MSG (Meteosat Second Generation) infrared dust index, computed from the brightness temperature differences of three satellite IR channels, is another useful tool to identify dust sources. Complementary, from low Earth orbit, NASA's SeaWiFS instrument records the biosphere and is monitoring the color of reflected light via satellite, providing a visible dust image over land surfaces.

2.4. Retrieval of Vertical Profiles

[7] The ground based profiles during the SAMUM-I campaign were taken with the Backscatter Extinction lidar-Ratio Temperature Humidity profiling Apparatus (BERTHA) at Ouarzazate [*Althausen et al.*, 2000; *Tesche et al.*, 2009]. Profiles are available for heights between 1 km and 7 km. They are cut above due to a rather noisy signal [*Müller et al.*, 2009a]. The airborne measurements taken aboard the DLR Falcon aircraft combined a nadir-looking High Spectral Resolution Lidar (HSRL) [*Esselborn et al.*, 2009] with extensive in-situ instruments [*Weinzierl et al.*, 2009] to probe the atmosphere in the Ouarzazate area between 0–11 km height. The vertical extinction coefficient of DREAM is calculated by means of the dust concentration in each model layer [*Pérez et al.*, 2006a] along the methods described in section 2.2.

2.5. Surface and Tropospheric Size Distribution

[8] Ground based particle number size distribution measurements were conducted at Tinfou ground station (situated 150 km southeast of OUZ at 30.33°N, 5.66°W) by means of a combination of a Differential Mobility Particle Sizer (DMPS) and an Aerodynamic Particle Sizer (APS). The respective mobility or aerodynamic size range was between 20 nm and 5 μm, respectively [*Schladitz et al.*, 2009]. Large particles between 4 μm and 500 μm were collected by two different impactor types [*Kandler et al.*, 2009]. The upper level aerosol size distribution was derived on constant altitude sequences without the presence of clouds aboard the DLR Falcon aircraft over the Ouarzazate region (same flight as for lidar measurements described above). Due to the physical limits of the measurement technique, particles larger than 30 μm are not taken into account [*Esselborn et al.*, 2009; *Weinzierl et al.*, 2009]. DREAM number size distribution was derived assuming sphericity and average particle density of 2.6 g/cm^3.

3. Results and Discussion

3.1. Dust Horizontal Distribution

[9] The period from May 16th to May 22nd 2006 is chosen for AERONET AOD comparison with special attention paid to May 19th and 20th since complementary ground-based and overflight data are available. The considered period is affected by a large scale dust event extending from southern Morocco to the Iberian Peninsula and the Mediterranean [*Knippertz et al.*, 2009]. SeaWiFS images for May 20th (Figure 1b) and MSG dust images for May 19th and 20th (Figures 1c and 1d) show a pronounced dust cover stretching along the African coast lining up to Italy in the Mediterranean. Both model scenarios succeeded to reproduce this pattern from a qualitative point of view (Figures 1g–1k). For quantitative comparison, AERONET Sun photometer AOD values and the Ångström exponent at four stations were chosen: Ouarzazate (OUZ), 30.94°N, 6.91°W; Tamanrasset (TMR - location closest to sources), 22.79°N, 5.53°E; Lampedusa (LMP - Mediterranean island), 35.52°N, 12.63°E; and Blida (BLI - located at the Mediterranean coast), 36.51°N, 2.88°E (Figure 1a). Ångström exponent above 0.6 indicates significant influence of fine anthropogenic aerosols. This is the case at LMP between May 16th and 18th (Figure 2a) and BLI between May 20th and 22nd (Figure 2c) where the model consistently simulates very low or zero dust conditions. In turn, high AOD values indicate dust as observed at LMP and OUZ on May 19th and 20th (Figures 2a and 2b). RESH shows excellent agreement while OPER shows underestimation at both sites. Also, RESH shows very good agreement at BLI from May 16th to 18th with underestimation for OPER. These results indicate that OPER's underestimation of AOD is due to inefficient transport of dust caused by the poor size bin resolution.

[10] Very high dusty areas over North Africa were tracked by MSG RGB product and the OMI AI, showing discrete dust plumes over southern Algeria, Mali and Mauritania as well as over the Bodélé depression in Chad on May 19th (Figures 1b and 1c). Note that although AI is a qualitative index that differs from AOD, OPER and RESH capture fairly well the general pattern (Figures 1g and 1j). Taking a closer look at the dust plume over south Algeria, dust emission at this source region is found to be more pronounced in OPER (Figure 1g) than in RESH (Figure 1j). At TMR, which is located slightly north, reverse conditions for OPER and RESH (Figure 2d) can be found with respect to the AOD values. Though the peak emission in RESH is lower, it overestimates AOD in TMR in contrast to OPER that corresponds well. This is outlining again that dust transport is more efficient in RESH due to improved transport bin resolution, but also that OPER performs well close to sources. Emission strength is weaker in RESH partly due to negative radiative dust feedback upon dust emission, caused by dust-induced stabilization in the plane-

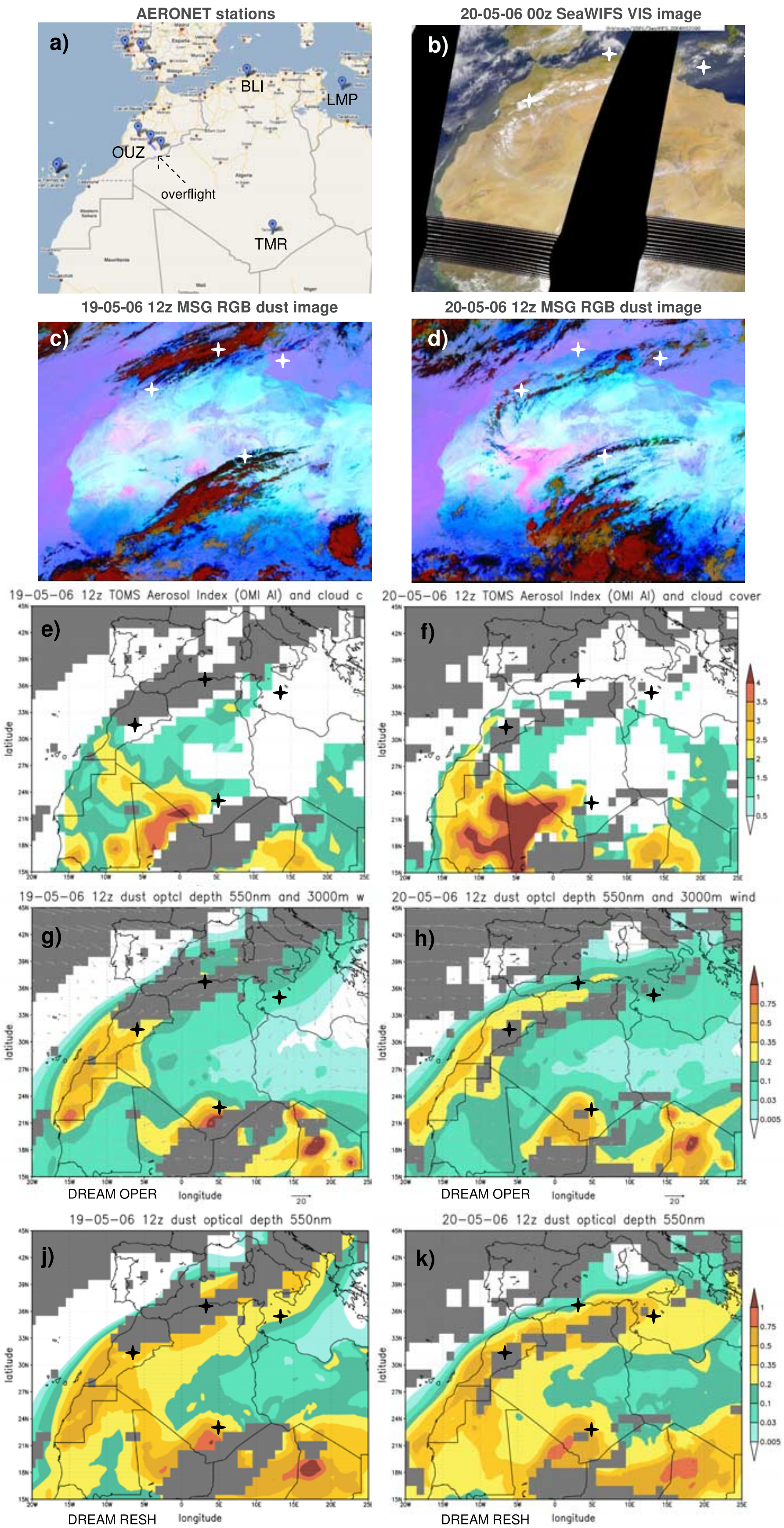

Figure 1. (a) AERONET stations, (b) SeaWIFS VIS image, (c, d) MSG RGB-dust images, (e, f) OMI-Aerosol Index, and model derived AOD ((g, h) OPER and (j, k) RESH) at May 19th and 20th for the North African domain. Gray areas in Figures 1e–1k refer to cloud cover.

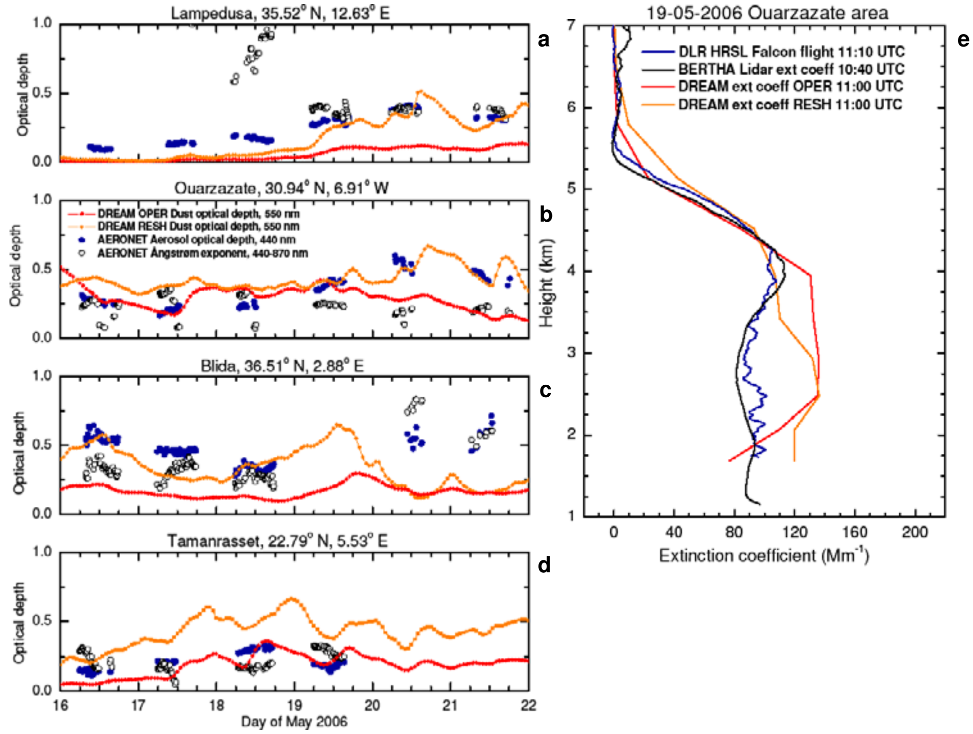

Figure 2. Model derived AOD (OPER and RESH), AERONET AOD and Ångström exponent for the period of May 16th to 22nd at (a) LMR, (b) OUZ, (c) BLI, and (d) TMR. (e) Modeled (550nm) and measured (532nm) extinction coefficient (above sea level) over the OUZ area.

tary boundary layer and thus a lowered surface friction velocity [*Pérez et al.*, 2006b; *Heinold et al.*, 2009]. Similar differences between OPER and RESH are encountered in the Bodélé and surrounding areas.

[11] Things appear to be less ideal on May 20th. MSG RGB image and OMI AI show a distinctive dust plume with AI > 4 over Mali and the eastern part of Mauritania (Figures 1d and 1f) which is poorly captured by the model (Figures 1h and 1k). This is due to an interesting synoptic evolution beginning in the afternoon hours of May 19th when deep moist convection were developing over north-eastern Mali. Continuing on May 20th, downdrafts from this convection formed a large haboob whose leading edge was spreading towards the north and the west. Dust mobilization occurred over a practically uninhabited region in northern Mali with no surface observations, thus analysis cannot be constrained in order to exactly represent the spatio-temporal distribution of moist convection [*Knippertz et al.*, 2009].

3.2. Dust Vertical Extinction and Size Distribution

[12] Figure 2e displays the modeled and observed vertical profiles of the extinction coefficient over Ouarzazate (OUZ). Note the good overlapping between the ground based BERTHA and overflight HSRL lidars [*Esselborn et al.*, 2009; *Heese et al.*, 2009; *Heinold et al.*, 2009; *Müller et al.*, 2009b; *Tesche et al.*, 2009]. These profiles are qualitatively and quantitatively fairly well captured by both model scenarios. They show very good agreement on the top of the dust layer and along the transition zone, and significant overestimation in the range of 2–3.5 km altitude. As already discussed, AOD measurements at OUZ on May 19th agree very well with OPER and RESH (compare Figure 2b) from a quantitative point of view, so do satellite retrievals (see Figures 1c and 1e) from a qualitative point of view, confirming the lidar observations.

[13] The surface size distribution at Tinfou (Figure 3e) [*Kandler et al.*, 2009; *Schladitz et al.*, 2009], is well reproduced for RESH on May 19th (11 UTC), except for very large particles. Their limited atmospheric residence time due to gravitational settling prevents them from being further uplifted. Highly variable surface wind speeds which affect measurements, may imply errors in the observed particle concentrations as discussed by *Schladitz et al.* [2009] and *Kandler et al.* [2009]. In turn, the lowest model layer reaches further up where large particles may not be present anymore what leads to the observed underestimation with respect to the average number size distribution. Note as well that RESH does not take particles larger than 20 μm into account. OPER matches satisfactorily the particle size spectra, given the coarse size categories which neglect smaller particles completely. Nonetheless, RESH demonstrates convincingly its ability to represent the atmospheric dust size spectra in a much better way in this case. The same applies for OPER and RESH at May 20th (12 UTC) (Figure 3f).

[14] One would expect good agreement regarding the size distribution at higher altitudes as well, but things turned out to be different as shown in Figures 3a–3d, providing the particle size distribution over OUZ at May 19th (11 UTC) and 20th (13 UTC) [*Weinzierl et al.*, 2009]. Large particles in the middle troposphere are strongly underestimated from OPER and RESH when comparing with number size concentrations measured during the Falcon overflight at 3.2 and

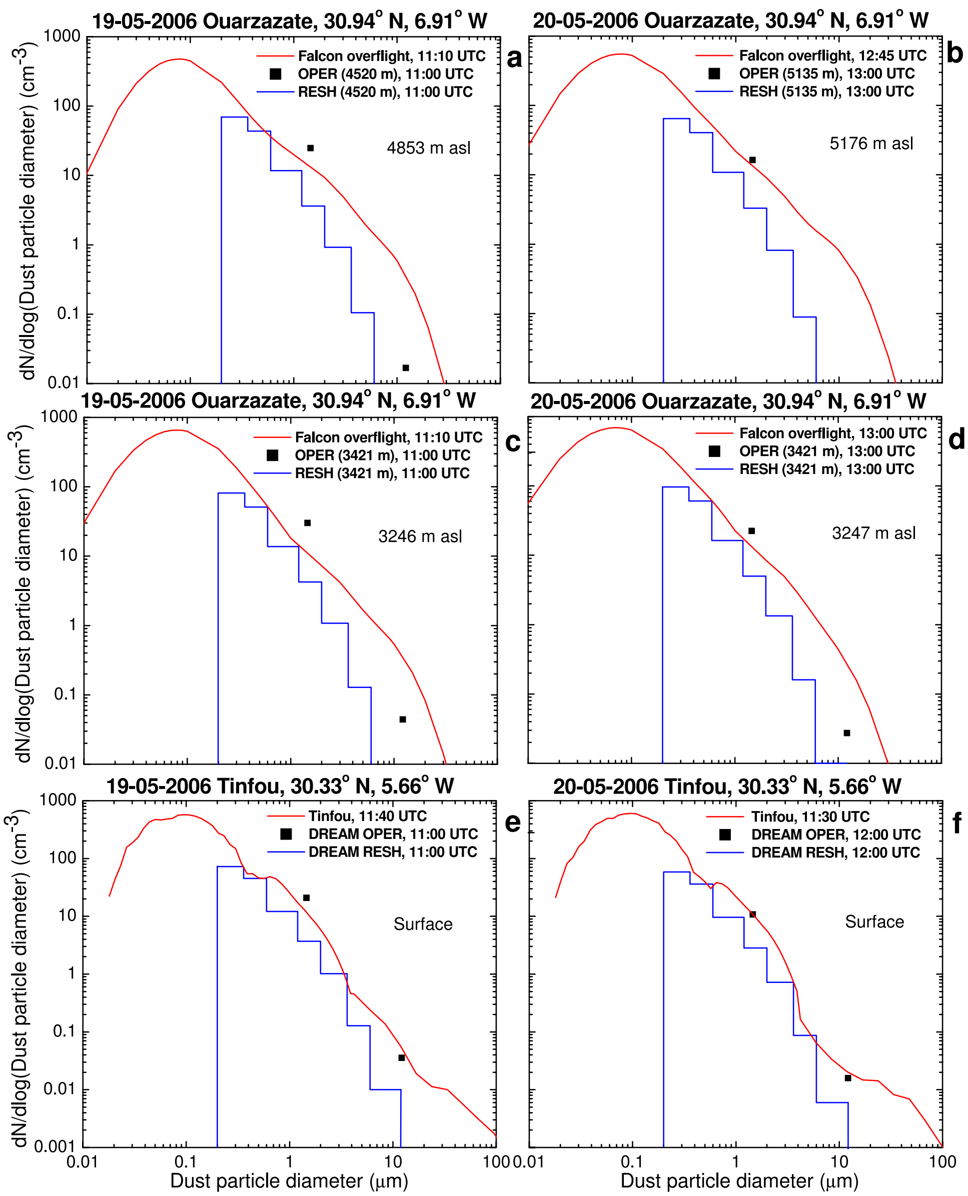

Figure 3. Measured (red line) and model derived particle size distribution (OPER black dots, RESH blue line) at May 19th and 20th 2006 over OUZ at (a, b) 5 km and (c, d) 3 km altitude, and (e, f) at the surface in Tinfou. Notice the truncated ordinate in Figures 3a–3d, causing the second size class for OPER to be out of range (Figure 3b).

5 km altitude at the same time. However, the modeled tropospheric number size distribution is in the same order of magnitude as the modeled surface number size distribution, in accordance with the vertical cross section of the extinction coefficient (see Figure 2e). In turn, having performed a closure study, *Weinzierl et al.* [2009] showed that in-situ measurements agree with the extinction profile at respective height levels. It could also be proven that the refractive index does not affect the derived particle number size distribution. Advected dust mixed above could explain the differences between measured surface and tropospheric number size distributions to a certain extent. Otherwise, the optical properties of dust for RESH are calculated with an average complex refractive index from GADS, which may alter depending on location, thus altering the extinction efficiency as well. Inaccuracies or simplifications of the dust emission scheme together with an incomplete data set of land cover and soil texture are further sources of uncertainty at all height levels. Conclusively, accordance of modeled and observed size spectra in upper regions of the atmosphere is not sufficiently obtained leaving space for further evaluation in order to achieve consistency.

4. Conclusions

[15] We have compared two DREAM model versions with experimentally derived results from the SAMUM-I campaign. Particular focus was put on May 19th and 20th 2006 when most measurements were available. Lidar observations and size distribution at surface levels are fairly well reproduced in RESH except for very large particles, due to the limited range of the model size distribution and the poor vertical resolution in the model. In the upper troposphere

large particles are more strongly underestimated. Dust at higher altitudes advected from non-local sources may explain these results.

[16] In general, fairly good agreement between model results, AERONET data, and satellite observations with respect to their horizontal and vertical distribution is obtained. It could be shown that RESH outperforms OPER from a quantitative point of view. Underestimation of dust transport in OPER is due to the poor size bin resolution, lacking efficient transport which is mainly driven by smaller particles. The spatio-temporal evolution of the dust plumes was not always sufficiently reproduced for both model versions. The disagreement is related to synoptic-scale meteorology which can not be accurately captured.

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References

Althausen, D., D. Müller, A. Ansmann, U. Wandinger, H. Hube, E. Clauder, and S. Zörner (2000), Scanning 6-wavelength 11-channel aerosol lidar, *J. Atmos. Oceanic Technol.*, *17*(11), 1469–1482.

Esselborn, M., M. Wirth, A. Fix, B. Weinzierl, K. Rasp, M. Tesche, and A. Petzold (2009), Spatial distribution and optical properties of Saharan dust observed by airborne high spectral resolution lidar during SAMUM 2006, *Tellus, Ser. B*, in press.

Heese, B., T. Dinter, M. Esselborn, A. Schladitz, and M. Wiegner (2009), Lidar profiles of dust optical properties over Tinfou, Morocco, during SAMUM 2006, *Tellus, Ser. B*, in press.

Heinold, B., et al. (2009), Saharan dust modelling during the SAMUM 2006 campaign, *Tellus, Ser. B*, in press.

Heintzenberg, J. (2009), Overview SAMUM 2006, *Tellus, Ser. B*, in press.

Kandler, K., et al. (2009), Size distribution, mass concentration, chemical and mineralogical composition, and derived optical parameters of the boundary layer aerosol at Tinfou, Morocco, during SAMUM, 2006, in press.

Knippertz, P., et al. (2009), Northern Sahara during SMUM 2006—A meteorological overview, *Tellus, Ser. B*, in press.

Müller, D., et al. (2009a), Mineral dust observations with EARLINET lidars during SAMUM 2006: The 12 to 22 May long-range dust transport event, *Tellus, Ser. B*, in press.

Müller, D., et al. (2009b), AERONET Sun photometer observations during SAMUM 2006: Comparison of mineral dust optical and microphysical properties to results from lidar and airborne in-situ measurements, *Tellus, Ser. B*, in press.

Nickovic, S., G. Kallos, A. Papadopoulos, and O. Kakaliagou (2001), A model for prediction of desert dust cycle in the atmosphere, *J. Geophys. Res.*, *106*(D16), 18,113–18,129.

Pérez, C., P. Jiménez, O. Jorba, M. Sicard, and J. M. Baldasano (2006a), Influence of the PBL scheme on high-resolution photochemical simulations in an urban coastal area over the western Mediterranean, *Atmos. Environ.*, *40*, 5274–5297.

Pérez, C., S. Nickovic, J. M. Baldasano, M. Sicard, F. Rocadenbosch, and V. E. Cachorro (2006b), A long Saharan dust event over the western Mediterranean: Lidar, Sun photometer observations, and regional dust modeling, *J. Geophys. Res.*, *111*, D15214, doi:10.1029/2005JD006579.

Schladitz, A., T. Müller, A. Massling, N. Kaaden, K. Kandler, and A. Wiedensohler (2009), Measurements of in situ optical properties at Tinfou (Morocco) during SAMUM 2006, *Tellus, Ser. B*, in press.

Tegen, I., and A. A. Lacis (1996), Modeling of particle size distribution and its influence on the radiative properties of mineral dust aerosol, *J. Geophys. Res.*, *101*(D14), 19,237–19,244.

Tegen, I., B. Heinold, M. Todd, J. Helmert, R. Washington, and O. Dubovik (2006), Modelling soil dust aerosol in the Bodele depression during the BoDEx campaign, *Atmos. Chem. Phys.*, *6*, 4345–4359.

Tesche, M., et al. (2009), Vertical profiling of Saharan dust with Raman lidars and airborne HSRL in southern Morocco during SAMUM, *Tellus, Ser. B*, in press.

von Hoyningen-Huene, W., T. Dinter, A. A. Kokhanovsky, J. P. Burrows, and M. Diouri (2009), Measurement of desert dust optical characteristic at Porte au Sahara during SAMUM 2006, *Tellus, Ser. B*, in press.

Weinzierl, B., A. Petzold, M. Esselborn, M. Wirth, K. Rasp, K. Kandler, L. Schütz, P. Koepke, and M. Fiebig (2009), Airborne measurements of dust layer properties, particle size distribution and mixing state of Saharan dust during SAMUM 2006, *Tellus, Ser. B*, in press.

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